The R2D2 project

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Introduction (1)

- The **nature of neutrino** is one of the critical missing pieces in our knowledge on the neutrino panorama.

Particle = Antiparticle

$\pi^0,\ \rho^0,\ \gamma,\ \ldots$

Majorana neutrinos

$\nu = \overline{\nu}$

↓

Lepton number violation

Particle ≠ Antiparticle

$K^0,\ D^0,\ \ldots$

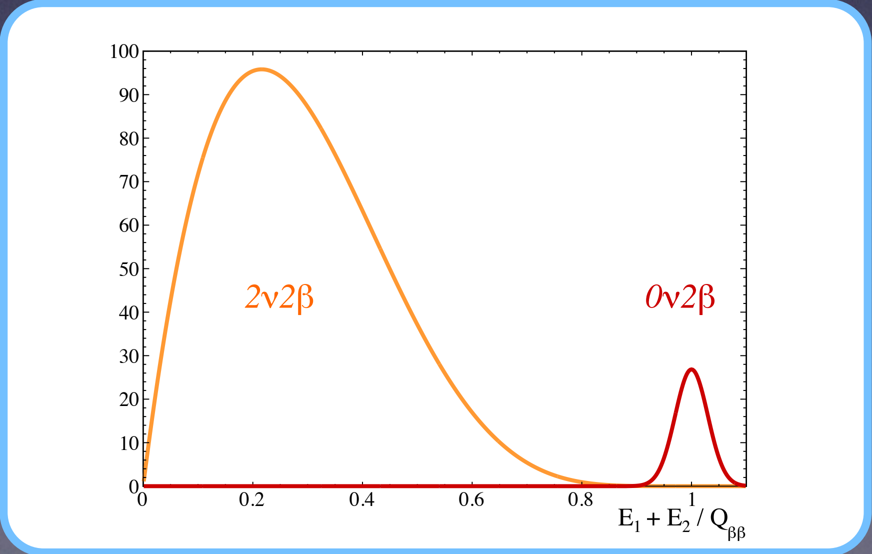
Dirac neutrinos

$\nu \neq \overline{\nu}$

↓

Lepton number conservation

- To demonstrate the Majorana nature of neutrino the most sensitive experimental way is an observation of the so called **0νββ decay**.
- The measurement relies on the observation of a peak corresponding to the $Q_{\beta\beta}$ of the reaction.



Introduction (2)

- The key ingredients to measure the peak **0$\nu\beta\beta$** are:
  - ➡ **Excellent energy resolution**. An excellent energy resolutions allow to select a narrow region of interest minimising the background counts in it and separating as much as possible the 0$\nu\beta\beta$ peak from the 2$\nu\beta\beta$ tail.
  - ➡ **Low background**. To reduce the background in the region of interest very pure materials have to be used and the lowest material budget has to be foreseen.
  - ➡ **Large isotope mass**. To enhance the signal large masses of isotope have to be used (order of one ton to cover the inverted mass hierarchy region). To do so the detector has to be scalable to such masses.

R2D2 is an R&D program aiming at the the development of a zero background ton scale detector to search for the neutrinoless double beta decay.

The R2D2 project (1)

- R2D2 stands for Rare Decays with Radial Detector.
- The idea is to use a high pressure Xenon gas TPC spherical detector to search for the $\beta\beta0\nu$ decay, profiting from the following features:
  - High energy resolution (goal of 1% FWHM at ^{136}Xe $Q_{\beta\beta}$ of 2.458 MeV)
  - Low detection threshold at the level of 17 eV i.e. single electron signal.
  - High detection efficiency (about 65% after selection cuts).
  - Simplicity of the detector readout with only one (or few in the upgraded version) readout channels.
- Preliminary studies show that we can have a detector with **very low background** (order of 2 events per year in 50 kg Xenon mass).
- The goal of the project is to prove that the energy resolution today achieved by semi-conductor detectors can be reached with a high pressure Xenon based TPC.
- The R2D2 project could provide physics results (limit on the $\beta\beta0\nu$ half life at the level of 10^{25} years) and at the same time pave the way for a following step i.e. a zero background detector at the ton scale.

The R2D2 project (2)

- A proto-collaboration has been recently formed.
- R2D2 is today approved as IN2P3 R&D to assess in particular the possibility to reach the desired energy resolution which is the major showstopper.

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The R2D2 Roadmap

If successful and funded

Depending on the results

Up to 7.9 kg (40 bars) Xenon prototype (no low radioactivity) to demonstrate the detector capability in particular on the energy resolution

50 kg Xenon detector (low radioactivity) with LS veto for first physics results to demonstrate the almost zero background

Going towards a 1 ton background free detector

Exploit the detector with other gases to cross check the background and possibly obtain interesting results selecting higher $Q_{\beta\beta}$, as well as the possibility to do tracking

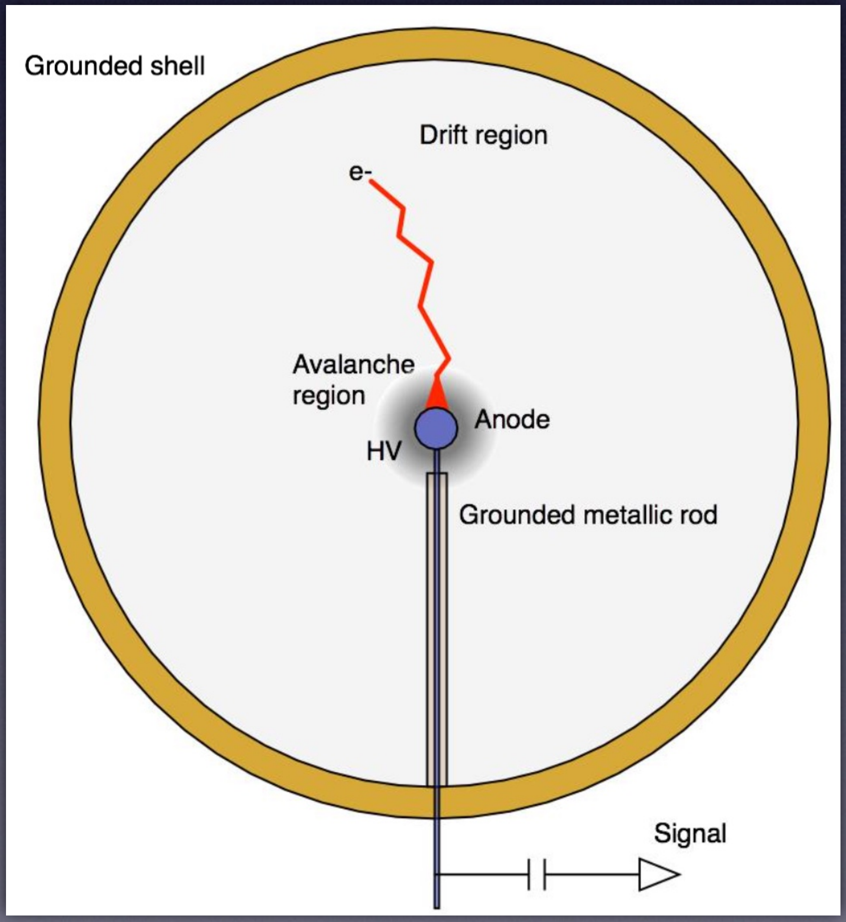
Under construction

Funded by IN2P3 R&D

Sensitivity studies carried out for this detector configuration

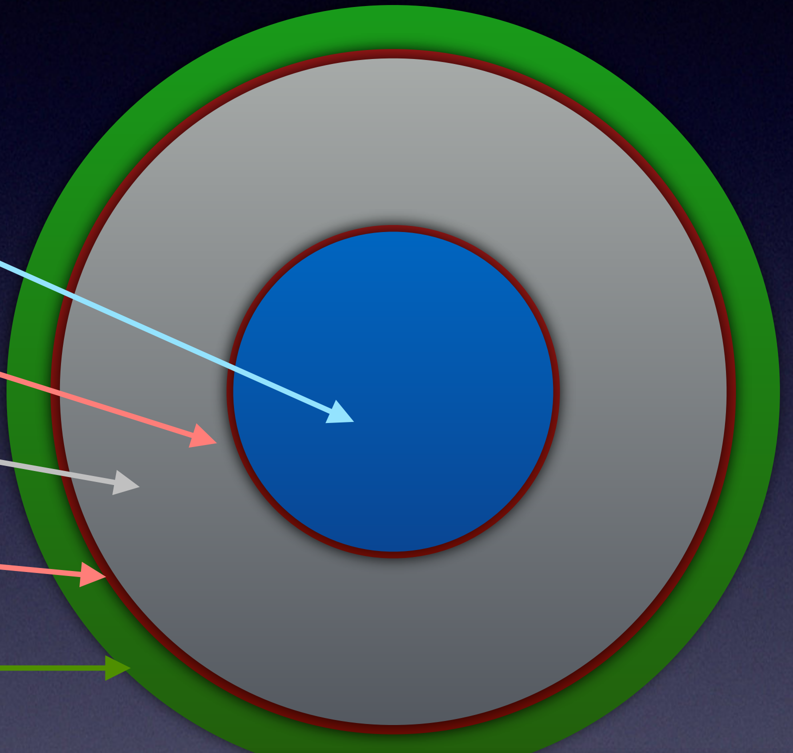
The detector

- The detector is a spherical Xenon gas TPC as proposed by Giomataris et al. and used today in the NEWS collaboration for the search of dark matter.
- The design was optimised for the background reduction in the $\beta\beta0\nu$ search with ^{136}Xe ($Q_{\beta\beta}$ of 2.458 MeV).
- A detail description of the carried out studies can be found in *JINST 13 (2018) no.01, P01009*.



Sensitivity studies

- The first step is a **full Monte Carlo simulation** to assess our capability to reject background and to evaluate the possible sensitivity on the searched signal.
- We considered a geometry including active and passive veto and a small mass of 50 kg of xenon corresponding to the foreseen prototype.



Xenon active volume

Mass of 50 kg

Radius of 37 cm

Pressure of 40 bar

This choice, based on the results of a pressure and radius scan, is driven by the need of containing at least 80% of the $\beta\beta0\nu$ electrons.

Liquid scintillator volume

Thickness of 1.5 m

Assumed to be LAB

The thickness is chosen in order to have a background rate below 0.1 events per year from the ^{208}Tl contamination of the liquid scintillator vessel.

Shielding volume

20 cm Lead

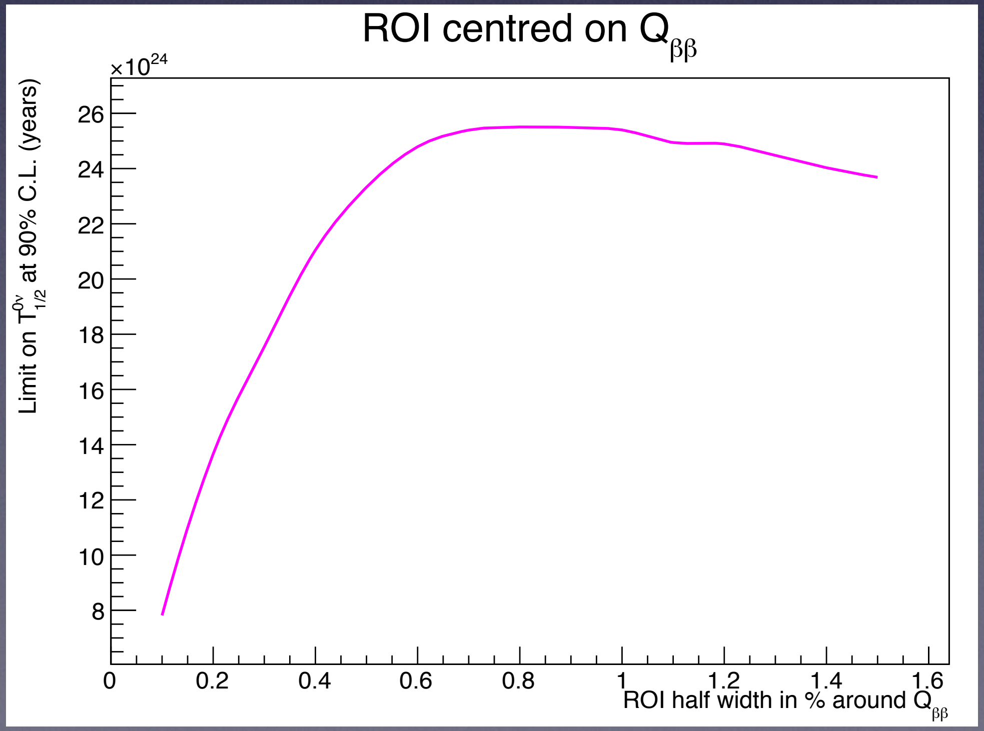
5 cm Copper

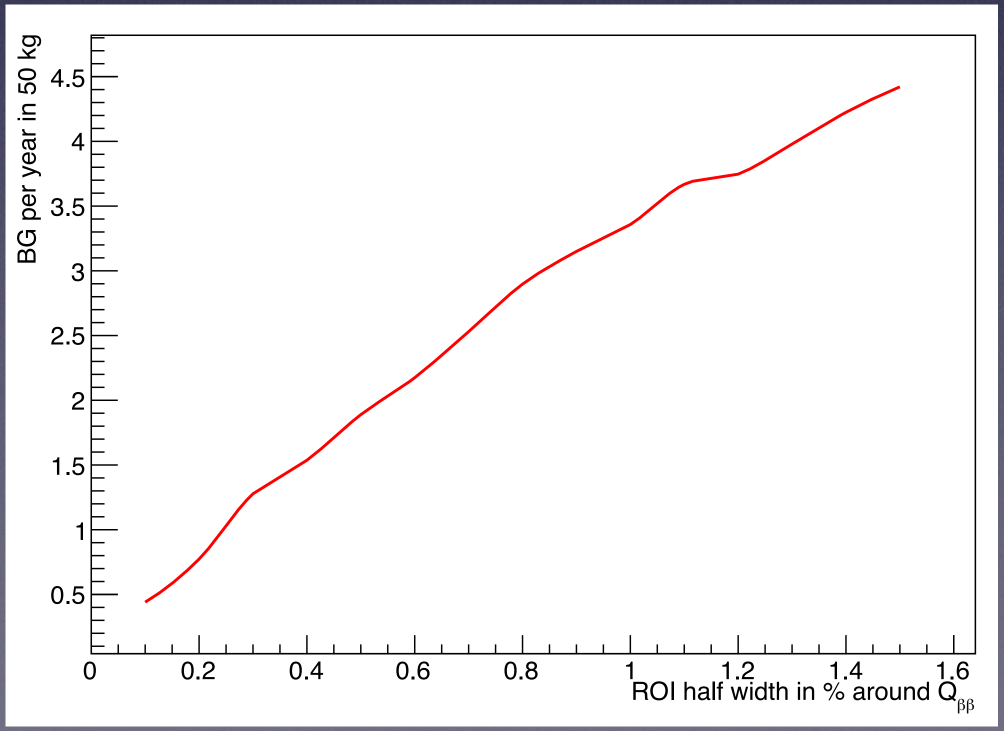
The choice was made to match the shielding used in measurements performed at LSM to have a reliable and less complicated MC.

Results

- We studied the intrinsic background coming from the vessel material and all the additional external background which we reduced at a level of less than 0.1 events per year.

- We could set a **limit on the $\beta\beta0\nu$ half life of 2.5 × 10^{25} years** with a **signal efficiency of 64%** and a **background at the level of 2 events per year** in 50 kg under the following assumptions:
  - Energy resolution of 1% FWHM at the $Q_{\beta\beta}$ of 2.458 MeV.
  - Optimized ROI of $Q_{\beta\beta}$ ± 0.6%.
  - Possibility of performing a radial energy deposition reconstruction.
  - A threshold as low as 200 keV for the liquid scintillator.
  - Copper activity of 10 μBq/kg.





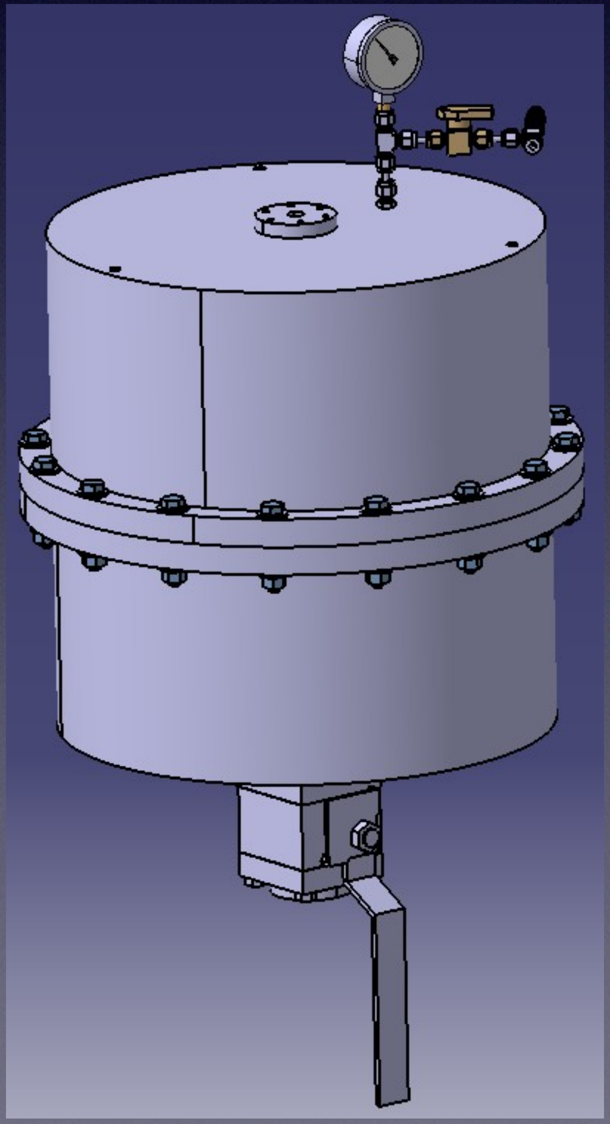
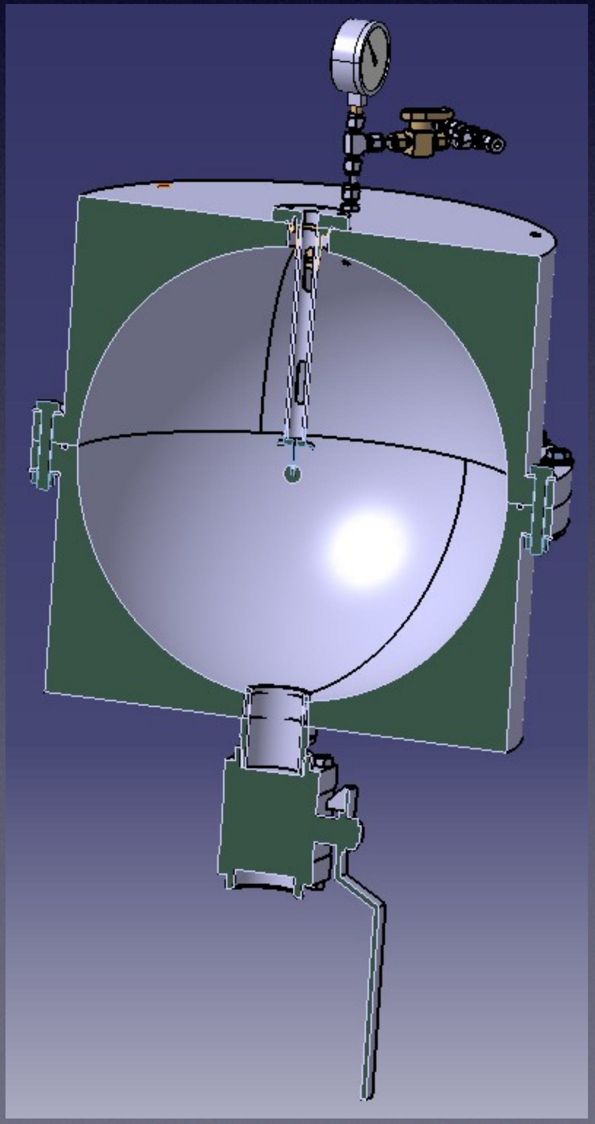
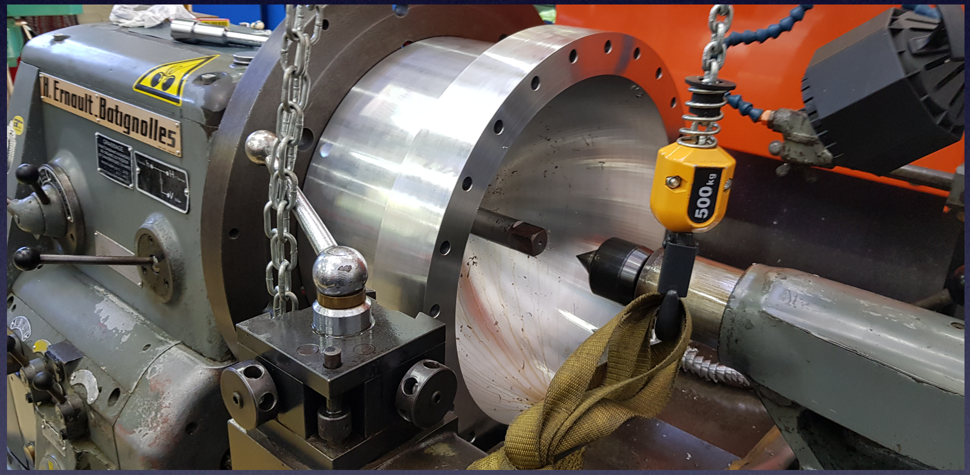
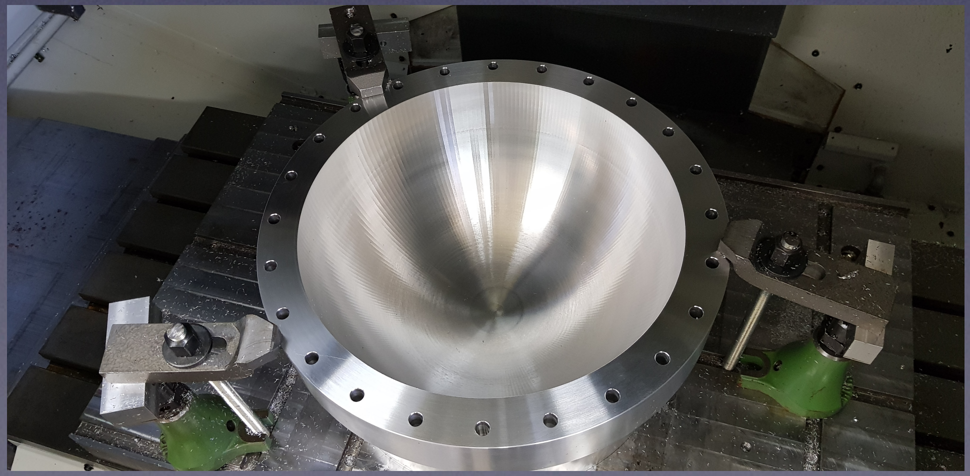
R2D2 R&D

- In 2018 the R2D2 was funded as R&D by the IN2P3.
- The main goal of the R&D is the demonstration that the desired energy resolution can be achieved.
- To do that the idea is to use a smaller detector (20 cm radius) made of Aluminium i.e. no low background but much cheaper.
- The setup is under construction at CENBG and we plan to start tests soon.

R2D2 R&D

Mechanics

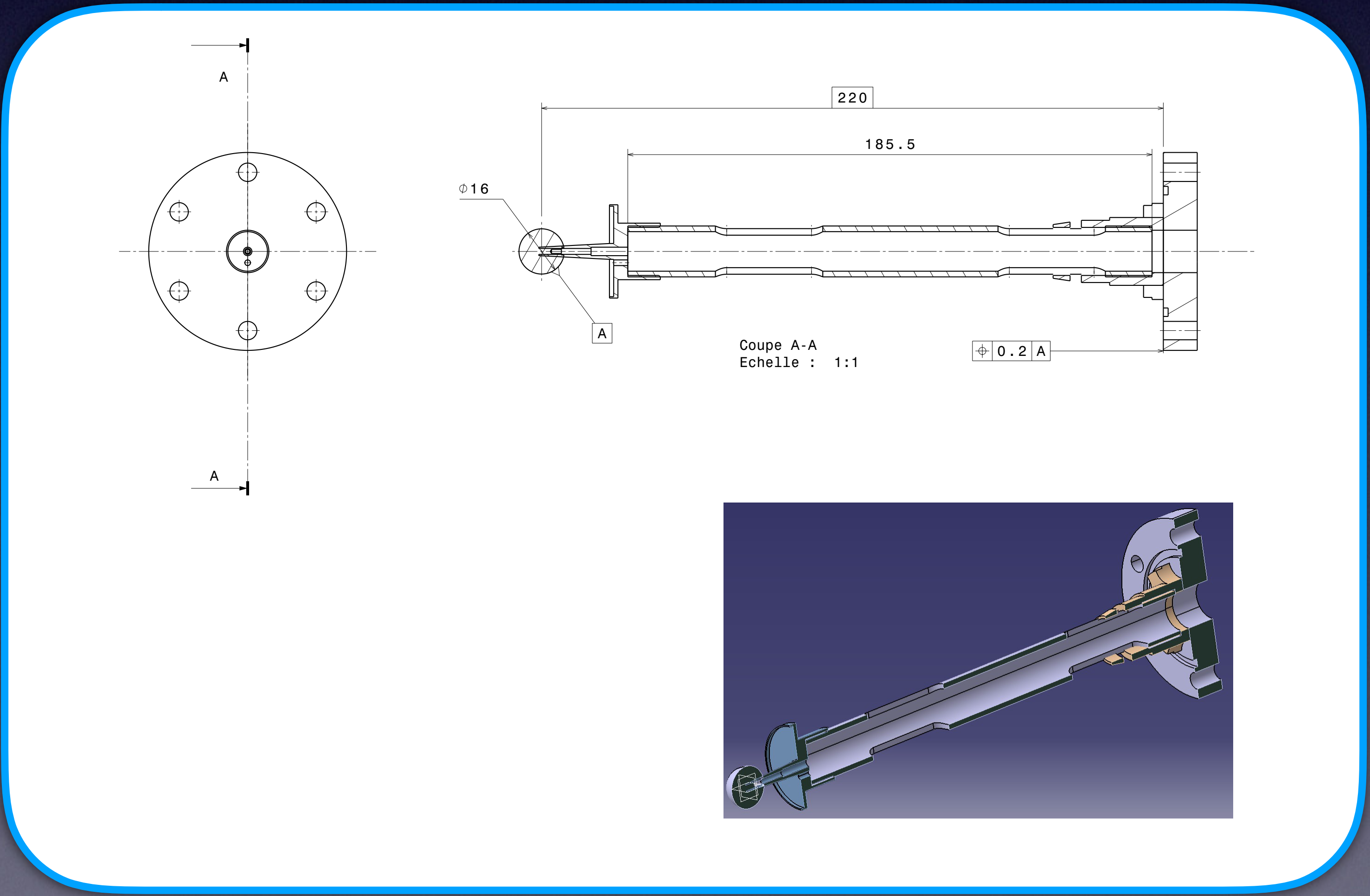
- The Aluminum sphere was conceived and built at the CENBG mechanical workshop.
- Ready to be used up to 4 bars without certification.

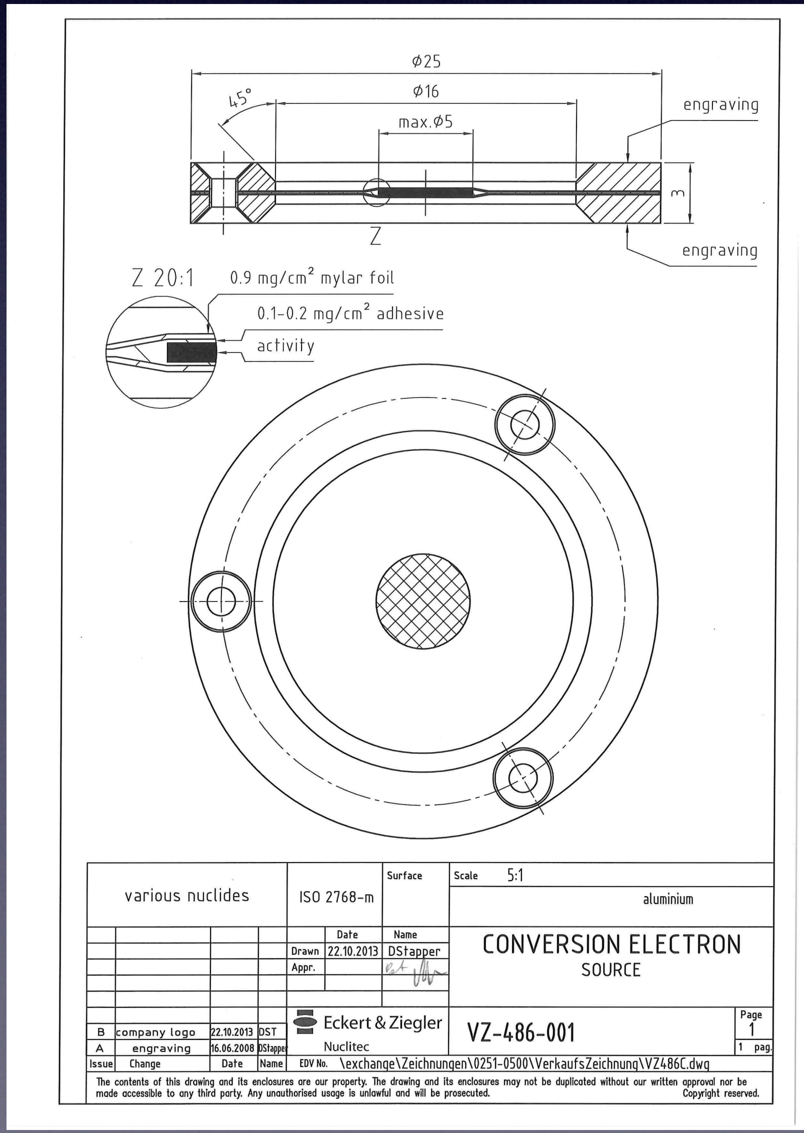





R2D2 R&D

Anode and source

- The central anode was built by CEA-LSM.
- A calibration source of Bi207 of 200 Bq has been bought for calibration.

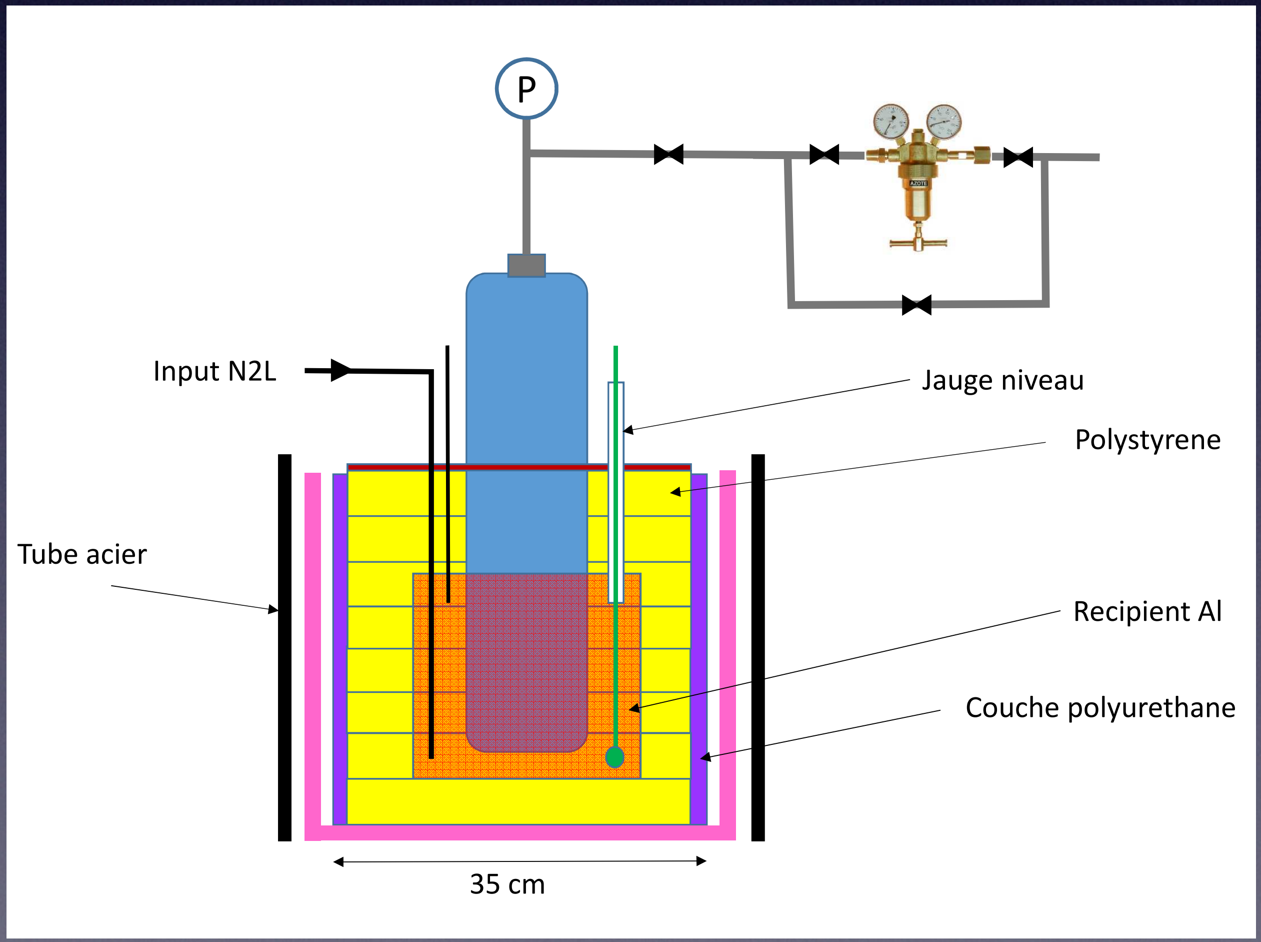




R2D2 R&D

Recuperation system

- Xenon recuperation system was conceived and built at CPPM.



R2D2 R&D

Roadmap

- **Fall 2018**: Commissioning of the detector with energy resolution tests using ArgonP2 (98% Ar + 2% CH4) at 1 bar.
- **Winter 2018**: Installation of the Xenon recuperation system and firsts tests with Xenon.
- **2019**: Mesure of energy resolution Vs pressure in Xenon.

  Studies on Xenon purification.

  Study of Xenon scintillation.

  Certification of the TPC for 40 bars.

  Optimization of the electronics and waveform exploitation studies.

  Development of the sensor (multiball included).

Developments (1)

- Once the first step pf the R&D is achieved, namely on the demonstration of the energy resolution at high pressure, a real low background prototype can be built to validate the background rejection.
- Several developments are under study and could be tested on the prototype.

Electronics

- The signal waveform analysis is a critical ingredient for a particle identification i.e. for background reduction.
- We need an electronics that allows for a signal waveform reconstructions without affecting the energy resolution.
- Custom made electronics are under developments at CENBG/CEA.

Materials

- Needless to say the activity of materials used has a critical impact on the background.
- We assumed a copper activity of 10 μBq/kg which is conservative considering that on the market copper with an activity of 1 μBq/kg can be found.

Developments (2)

Light readout

- The radial position reconstruction is today based on a waveform analysis (basically the width of the signal normalised by its amplitude).
- The knowledge of the T0 given by the Xenon scintillation would be an important piece of information to have a more precise position reconstruction.
- In addition it would make the coincidence with the external liquid scintillator veto signal much shorter and easier.
- Given the impossibility to have PMT directly in the liquid scintillator sphere, and the difficulty to extract the light with fibers, an option of deposing small regions of photocathode is under study.

Geometry

- A fundamental question to answer is "is a sphere the best geometry?".
- To assure the homogeneity of a central wire could be easier with respect to a spherical anode.
- The drawback could come from the edges effects.

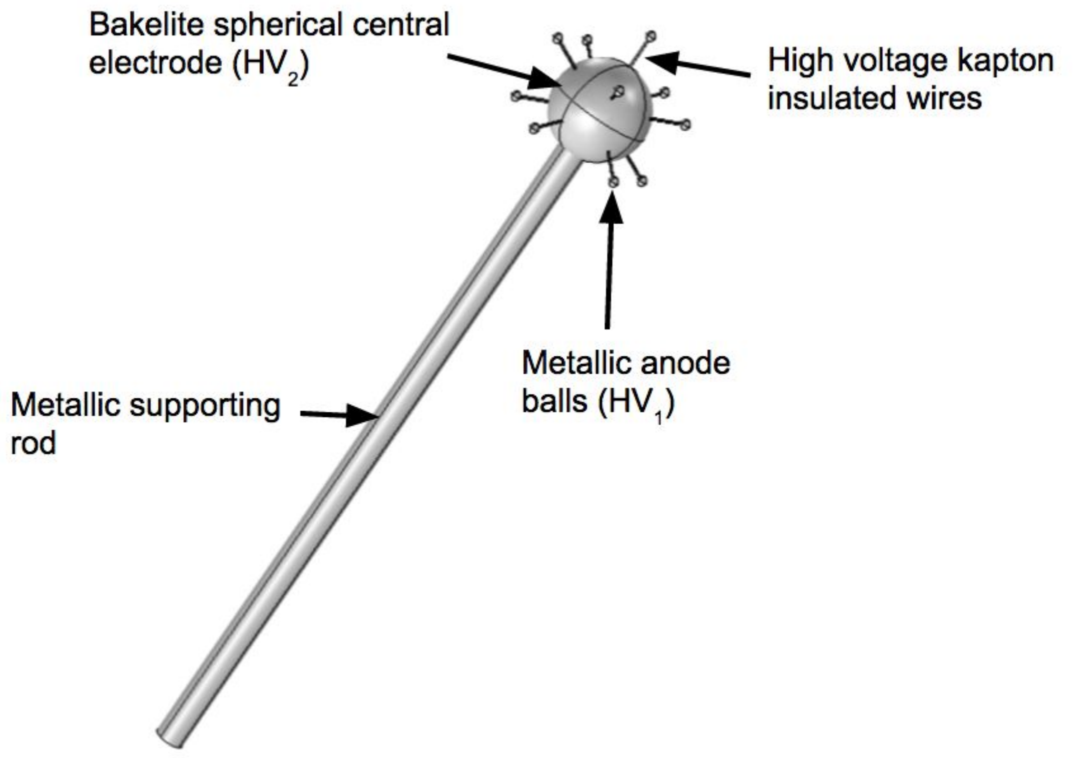
Gases

- The use of different gases in the same TPC (i.e. same background sources) could be an advantage to understand and benchmark the background.
- In addition gases with $\beta\beta$ emitters at higher $Q_{\beta\beta}$ would result in a smaller background.

Developments (3)

Central sensor

- High pressure and large spheres require a high voltage on the central anode.
- It seems that a reasonable limit before reaching technical difficulties is about 10 kV.
- A solution might come from a multi-ball readout (*arXiv:1707.09254*): with a smaller HV on each anode we could have the same field far from the anode and a higher amplification with respect to a single central ball.
- The anodes could be read independently giving a coarse detector segmentation (i.e. **coarse tracking**) which could result into an additional handle for background rejection (studies in progress).



Status and outlook

- The R2D2 proto-collaboration has been formed and the R&D has been approved by IN2P3.
- Preliminary studies showed that we could have competitive sensitivity with small masses and **potentially zero background detectors with large masses**.
- One of the advantages of such a detector is the possibility to use different gases in the same detector. If the technology will be proven successful the use of Xenon will be only a first phase of a more complete project.
- An R&D program has started with the main goal of assessing the achievable energy resolution, which is the first possible showstopper.
- Depending on the success of the R&D we hope to move on in order to build a prototype allowing for real physics results.

Interested people are welcome to join the project